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Mechanical Behavior of Aluminum Tubular Columns Filled with Steel Fiber Reinforced Concrete, "An Experimental Study"

Harith Al-Salman[a] *, Sara Sh. Alhilali[b], Alaa Hassoon[b]

[a] Department of Architectural Engineering, College of Engineering, University of Babylon, Babylon, Iraq.

[b] Civil Engineering Department, College of Engineering, University of Al-Qadisiyah, Diwaniyah, Iraq.

Keywords:

Concrete-Filled Aluminum Tubes (CFAT); Steel Fiber Concrete (SFC); Axial Load Behavior; Ductility Enhancement.

Highlights:

- *Enhanced Structural Performance: The addition of steel fibers to concrete in aluminum tubes increased stiffness by 13.7% to 74.1% and peak load capacity by 15.6% to 45.6%, demonstrating improved load-bearing capabilities under axial compression.*
- *Improved Ductility: Steel fiber reinforcement significantly boosted ductility, with enhancements ranging from 9.1% to 42.4%, allowing the composite columns to deform more without failure.*
- *Optimal Fiber Dosage and Failure Mitigation: The best results occurred at 1% fiber volume fraction, where higher amounts reduced efficiency due to clustering; fibers also prevented tearing in the aluminum shell by limiting lateral expansion and providing better confinement.*

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*Corresponding author:

Harith Al-Salman

Department of Architectural Engineering, College of Engineering, University of Babylon, Babylon, Iraq.

Abstract:

Concrete-filled aluminum tubular columns present a good composite system by combining the excellent corrosion resistance and adequate yield strength of aluminum with the filling ability of concrete, of better compression strength. This study investigated the behavior of steel fiber reinforced concrete (SFRC)-filled aluminum tubes (CFATs) under axial loading. Five specimens, each measuring 1000 mm in height and having square hollow aluminum parts of 100 x 100 x 3 mm, were made and put through axial compression testing. Concrete was mixed with steel fibers at fractions of volume of 0.5%, 1.0%, and 1.5% to assess the impact of the steel fibers on ductility, stiffness, and load-bearing capacity. The results showed that adding steel fibers increased stiffness and peak load by 13.7% to 74.1% and 15.6% to 45.6%, respectively. Furthermore, ductility improved significantly, with increases ranging from 9.1% to 42.4%. The optimal performance was achieved at a fiber content of 1%. Higher dosages resulted in diminished structural efficiency, likely due to fiber clustering and reduced homogeneity. Notably, in specimens without fibers, tearing at peak load was observed, attributed to lateral strain-induced tensile stresses in the aluminum shell. The inclusion of steel fibers effectively mitigated this issue by limiting lateral expansion and enhancing confinement.

INTRODUCTION

Recently, the use of hollow aluminum tube columns has increased owing to the adequate strength, low self-weight, and high corrosion resistance [1]. However, the low Young's modulus of aluminum experienced buckling failure [2]. Concrete-filled aluminum tube CFAT columns represent an acceptable solution to overcome such problems by combining the advantages of both materials, that the full support of concrete through column height prevents or delays the local buckling, while the aluminum tube introduces good constraint for lateral concrete strain, which leads to additional strength and better ductility [3]. Steel fibers and concrete were mixed to improve ductile fracture, preventing new fractures from forming, preventing or reducing the spread of preexisting fissures, and generally increasing ductility, strength, and longevity [4].

Conducted a study to evaluate how variations in concrete compressive strength and the diameter-to-thickness (D/t) ratio influence the axial performance of concrete-filled aluminum tubular (CFAT) columns. Their results demonstrated that infilling the aluminum tubes with concrete significantly enhanced their load-bearing capacity. However, for CFAT columns with lower D/t ratios, increasing the concrete strength from 40 MPa to 70 MPa had only a marginal effect on axial capacity when compared to columns with moderate or higher D/t ratios [5]. However, using concrete with a compressive value of 100 MPa significantly boosted the columns' capacity to carry loads [6]. The concrete's compressive strength improved the CFAT columns' strength and behavior [7]. When the length-to-depth L/D ratio was beyond 7, there was no discernible impact on the columns' overall behavior or load-carrying capability. The axial capacity increased by 16 to 224% when CFAT was used instead of hollow columns [8]. Although the increase in column height by about 56% decreased the ultimate load by 1 to 6% the higher slenderness ratio experienced a lowered load carrying capacity.

Experimental research has examined the behavior of aluminum columns loaded with lightweight concrete [9]. Columns with different concrete compressive strengths were tested under two loading scenarios: the first was composite action, in which the load is applied on the concrete and aluminum simultaneously, while the confinement action was performed by applying the load on the concrete only, so the aluminum tube will introduce indirect strength through confinement. According to the findings of the tests, using lightweight concrete raised the ultimate load by 30 to 86% for confinement action and 50 to 114% for composite action.

An analytical study was conducted on the behavior of CFAT columns under axial compression, considering the nonlinearities of aluminum and concrete. The impact of depth-to-thickness ratio, aluminum ratio, and concrete strength was assessed. According to the finite element results, the ultimate load increased as the yield strength of concrete or aluminum increased. Additionally, columns with lower aluminum ratios demonstrated higher strength and ductility, as the lighter thickness provided better confinement, outperforming the axial strength [10]. The effects of confinement, depth-to-thickness ratio, and high-strength concrete on lateral pressure were numerically investigated for circular CFAT columns [11]. The study reported that the unique properties of aluminum tubes enhanced the ultimate stress of concrete. Moreover, the use of high-strength concrete increased the ultimate load but reduced ductility. In contrast, increasing the depth-to-thickness ratio led to a reduction in load-carrying capacity.

In another study, six specimens and four matching hollow tubes were tested under axial compression to assess the impact of the additional inner steel tube and concrete strength on the behavior of CFAT columns. The test results showed that the inner steel tube effectively enhanced the ultimate load, post-peak ductility, and failure mode with a strength index greater than 1 [12]. In another study, ten specimens with similar and different circular and square inner and outer tubes were tested under a four-point loading system, and the behavior of double-skin CFAT columns was examined. The results showed a slight increase in flexural capacity with the increase in concrete strength, with a ductile failure accompanied by local buckling and tensile failure occurring in the circular columns with the maximum diameters [13].

The impact of eccentricity on the load was examined [14]. The impact of section form and slenderness ratio was assessed using tests on eighteen specimens. The internal concrete had a significant impact on the failure mode and capacity, in conclusion. While the concrete contained by the round columns remained undamaged, the interior concrete of the square columns was crushed. This is because the circular tubes offered a more effective limit for the internal concrete. Additionally, weak confinement to the internal concrete was discovered as a result of the rise in load eccentricity.

To study the behavior of double skin circular concrete-filled aluminum tubular studs, twelve specimens were prepared and then axially tested [15]. Results discussion revealed that concrete strength, diameter to thickness ratio, and hollow ratio had a significant effect on the ultimate load capacity of the tested columns.

Compared to concrete-filled steel tube CFST columns, very few studies have been conducted on CFAT columns. More research is still required to solve the issue. Additionally, there hasn't been much research on how aluminum columns filled with steel fiber concrete SFC behave is very rare; thus, this study will concentrate on how employing regular steel fibers with varying volume fractions affects the behavior of CFAT columns. The overall behavior in terms of ultimate capacity, ductility, stiffness, and strength indices is anticipated to be improved by the usage of SFC.

METHODOLOGY

Specimens

Five aluminum tubular columns with a ratio of width to thickness equal to 33.33 [16]. The first column was hollow without any filling material, and the second was filled with normal strength concrete, while the rest were filled with steel fiber concrete SFC of 0.5, 1.0, and 1.5% volume fractions as illustrated in Figure 1. The geometric properties of the tested columns are given in Table 1.

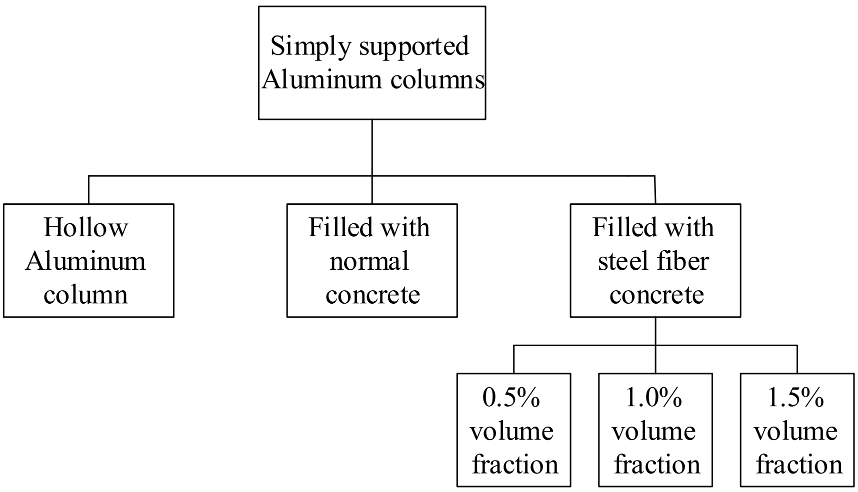

Figure 1. Test matrix

Table 1. Specimen's details

Specimen symbol	Width (mm)	Depth (mm)	Thicknes s (mm)	Height (mm)	Filling material	Volume fraction (SFC) %
C_1	100	100	2.8	1000	-	-
C_2	100	100	2.8	1000	NC	0
C_3	100	100	2.8	1000	SFC	0.5
C_4	100	100	2.8	1000	SFC	1
C_5	100	100	2.8	1000	SFC	1.5

Materials

Square hollow aluminum spacemen of 1000 mm length were used in this study to evaluate mechanical properties. Three segments from the web canter of untested specimens through the longitudinal direction were prepared and tested according to ASTM [17]. Table 2 provides the values of the aluminum segments' properties.

Table 2. The physical properties of Aluminum columns

Segment No.	Yield stress (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
1	225.3	251.7	69.1
2	223.4	252.1	68.3
3	219.6	241.5	66.4

The concrete mixture was made using ordinary Portland cement that was purchased from a nearby store and met the requirements of Iraqi Specifications [18]. Crushed gravel up to 14 mm in size and natural sand met Iraqi specifications [19] and were included in the concrete mixture. In this experiment, steel fibers with a length-to-diameter ratio of 75 were utilized. Table 3 displays the physical characteristics of steel fibers.

Table 3. The physical properties of steel fibers*

Specific Density (g/cm³)	Diameter (μm)	Length (mm)	Aspect Ratio (l/d)	Tensile strength (MPa)
7.8	160	12	75	2700

* Supplied by the manufacturer.

The target compressive strength was the minimum that can be used for construction purposes (17 to 18 MPa). Four concrete mixes were prepared using the illustrated materials; the first was without steel fibers, while the rest of the mixes were the same as the first mix, but steel fibers of 0.5, 1, and 1.5% volume fractions were used. Table 4 provides the mix proportions.

Table 4. Concrete mixes details

Mix	Cement (kg/m3)	Sand (kg/m3)	Gravel (kg/m3)	Steel fibers (kg/m3)	Water (Lit./m3)	Super plasticizer (Lit./100 kg cement)
NC	400	667	1000	-	150	0.8
SFC1	400	667	1000	39	150	1
SFC2	400	667	1000	78	150	1
SFC3	400	667	1000	117	150	1

Casting of specimens

The casting process was performed in the Concrete laboratory in the College of Engineering, University of Al-Qadisiyah, at a temperature of less than 30⁰ °C. The aluminum columns were placed vertically, then the materials were mixed while they were dry, and the SF was added to the materials and mixed with them before adding water. After that, the water was mixed with the required superplasticizer of each mix and added to the mixture. After preparing the mixture, the empty columns were poured according to each model. A vibrator was used to homogenize the mixture and fill the following spaces, as shown in Figure 1. After pouring the model, samples were also taken from the cubes and cylinders to examine the properties of the concrete [20]. After the cast of specimens was complete, the columns were covered from the top to maintain the water, and then cured for 28 days with water.

a. Vibrating of filling concrete b. Cubes and cylinders

Figure 2. Casting of the CFAT column

Test setup

A loading frame with a hydraulic actuator of 10,000 kN capacity and simply supported ends was used to name the specimens before the test, as seen in Figure 2. The axial and lateral displacements at each load increment during the test were recorded manually using three dial gauges with a 0.01 mm precision and a 25 mm capacity were fixed at the bottom and mid-length of two sides. The load was supplied at a rate of 10 kN.

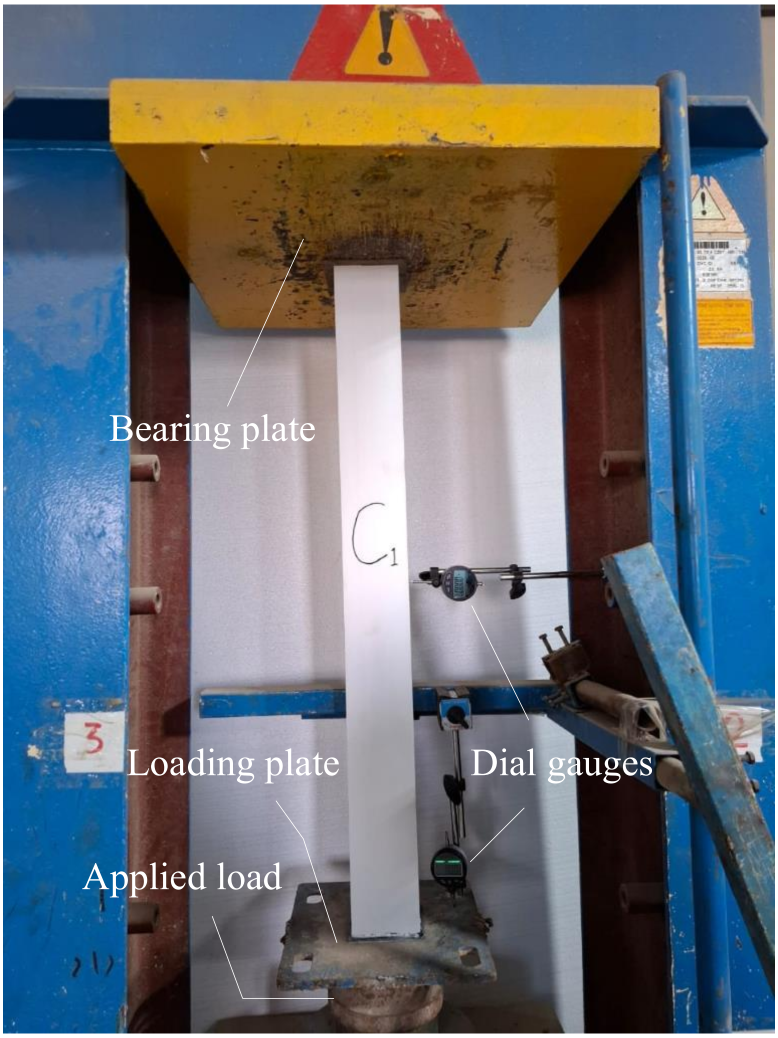

Figure 3. Test setup

RESULTS AND DISCUSSION

Concrete's mechanical characteristics

Three cubes and two cylindrical specimens were sampled for each mix during the specimen casting process in order to assess the normal and steel fiber concrete's compressive and splitting tensile strengths. Table 5 provides the average values.

Table 5. Mechanical properties of concrete

Mix	Compressive strength f_{cu} (MPa)	Splitting tensile Strength f_{ct} (MPa)
NC	22.3	2.32
SFC1	27.6	3.89
SFC2	35.1	4.31
SFC3	25.4	2.86

As many studies have been conducted [4,21,22], it is evident that the addition of steel fibers of 0.5, 1, and 1.5% enhanced the compressive strength by 23.8, 57.4, and 13.9% respectively, while the improvement of splitting tensile strength is 67.8, 86.2, and 23.3% respectively. The capacity of steel fibers to bridge is responsible for the strength improvement, since it delays the formation, propagation, and growth of cracks. Furthermore, steel fibers can efficiently disperse internal stresses, allowing the material to absorb more energy and support heavier weights before failing. Nevertheless, a significant reduction in strength appeared when an excessive volume fraction is used due to the balling or nesting resulting from the less uniform concrete mix [23].

General behavior

Each column was tested till final failure was observed, and the axial and lateral displacements were carefully documented. A synopsis of the experimental test results is provided in Table 6, while Figure 3 illustrates the failure pattern of the tested columns.

Table 6. Summary of test results

Specimen symbol	Filling material	Steel fibers (VF) %	Ultimate load (kN)	Failure mode
C_1	Hollow	-	21	local buckling at the top
C_2	NC	0	90	local buckling at the bottom and tearing at one of the corners
C_3	SFC	0.5	114	local buckling at the bottom
C_4	SFC	1	131	local buckling at the top
C_5	SFC	1.5	104	local buckling at the top

The ultimate capacity of the composite section was increased by 328.6% when regular concrete was used as a filler in column C2 as opposed to hollow column C1 because of the concrete's increased stiffness, its capacity to postpone local buckling to a high load, and the compression strength that the aluminum tubular provided. This is the same as what most previous researchers in this field have reached [5–9]. In addition, the use of SFC with a volume fraction of 0.5, 1, and 1.5% in specimens C_3, C_4, and C_5 experienced load carrying capacities more than C_2 which filled with normal concrete by 27.6, 45.6, and 15.6%, respectively that steel fibers usually raised the compressive and tensile strength of concrete by providing more ductility and stiffness in elasto-plastic phase. This phenomenon has been enhanced by the confinement of the aluminum section.

Figure 4. Failure patterns of the tested columns

The most observed failure pattern was local buckling; column C_1 experienced local buckling earlier. The use of normal concrete significantly delayed the local buckling, as the filling material that exists in the hollow section reduced the unsupported area on all sides throughout the column height. However, tearing at one of the section corners after the local buckling occurred that the lateral strains in concrete exceeded the tensile strength of aluminum at weak corner zones.

Although the failure loads of columns C_3, C_4, and C_5 filled with SFC of 0.5, 1, and 1.5% volume fraction were higher than C_2, no tearing appeared at corners because the use of steel fibers enhanced the behavior of specimens to withstand more loads and absorb most of the lateral strains, which reduce the tensile stresses resulted in aluminum due to confinement. However, the nonhomogeneous concrete resulting from balling or nesting of high steel fiber content in column C_5 led to a weak bond with aluminum faces and may provide free, unsupported small areas, which in turn led to the lowest capacity compared with C_3 and C_4.

Load deflection response

The axial and lateral displacements were recorded at each load increment till failure. Load displacement polynomials of the tested columns are shown in Figures 4 and 5, respectively.

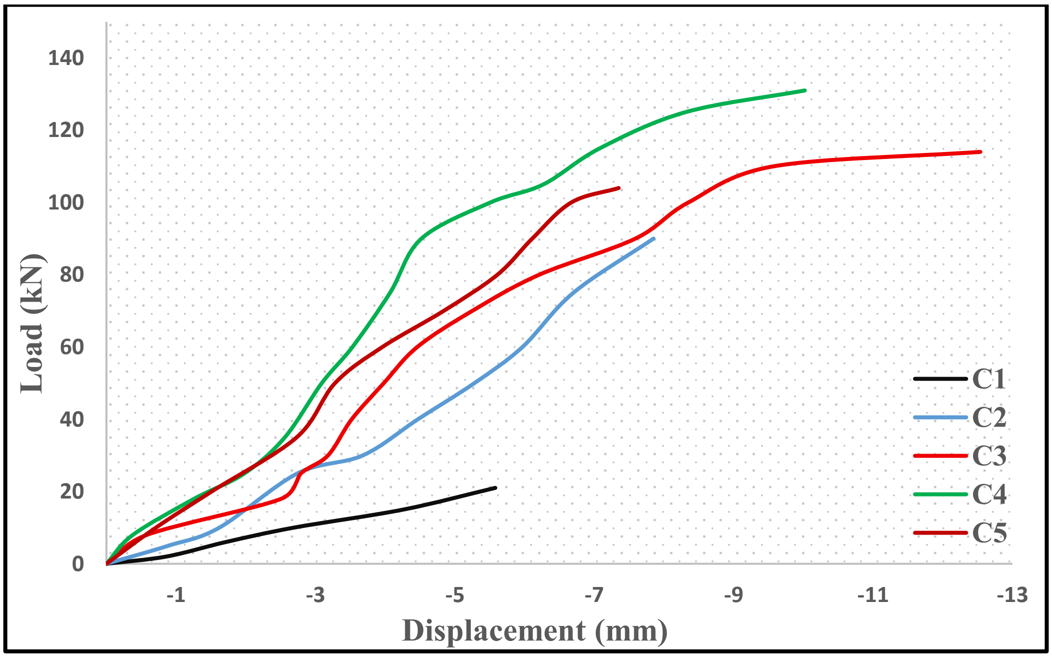

Figure 5. Load-axial displacement curve of the tested columns

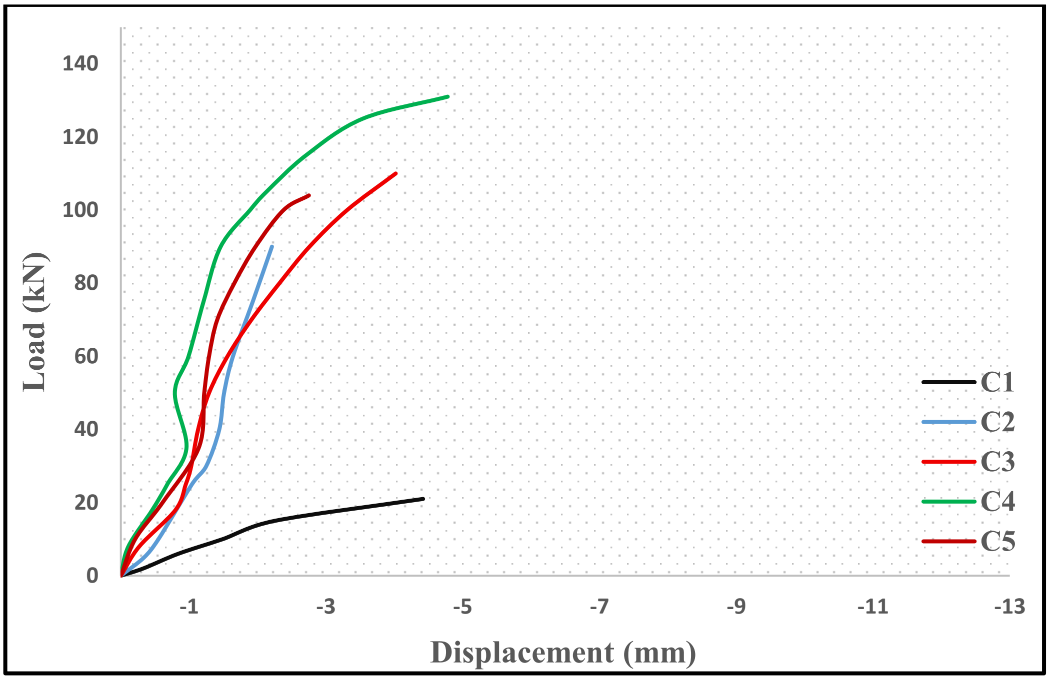

Figure 6. Load-lateral displacement curve of the tested columns

At ultimate loads, the axial displacements of normal and steel fiber concrete are higher when compared with the hollow one, as the reference specimen experienced local buckling failure earlier. However, for column C2 filled with normal concrete, the axial displacement decreased by 60.7% when compared with column C1's ultimate load due to the high additional area provided by the concrete. In addition, steel fiber concrete of 0.5, 1, and 1.5 % decreased the axial displacements by 55, 77.4, and 72.9% respectively, which is rather better than normal concrete because of the bridging ability of steel fibers, which reduces the lateral strains under loading. [24] has been reached for a similar behavior under different loading configurations.

On the other hand, the lateral mid-height displacements for columns filled with normal concrete decreased by 50% so the increase in the second moment of the filled columns was significantly higher when compared with the increase in the cross-sectional area, so the flexural stiffness will increase more than its axial counterpart. Nevertheless, the decrease in SFC is 9 to 37.8% which is less than that of normal concrete because columns filled by SFC experienced higher loads than normal concrete, which required more deformations, especially in the elasto-plastic phase up to failure. This was also concluded by [25].

Ductility index

Ductility refers to the member's ability to withstand additional loads and experience a nonlinear deformation response. Theoretically, the ductility index for a strengthened member can be approximately obtained for the load displacements polynomial by dividing the displacement at 0.95 percent of ultimate load by the corresponding value at 0.67 represents the ductility index [26]. Table 7 provides the ductility indices of the tested columns.

Table 7. Ductility indices of the tested columns

Specimen symbol	Displacement at 0.67 of peak load (mm)	Displacement at 0.95 of peak load (mm)	Ductility index
C_1	4.01	5.31	1.32
C_2	5.97	7.46	1.25
C_3	5.91	9.42	1.59
C_4	4.41	8.31	1.88
C_5	4.84	6.98	1.44

As expected, using of SFC raised the ductility indices of columns C3, C4, and C5 by 27.2, 50.4, and 15.2% when compared with column C2 and by 20.5, 42.4, and 9.1% when compared with column C1such a conclusion reached by [27,28] owing to the ability of steel fibers to redistribute the loads among the nonhomogeneous concrete particles, reduced lateral strains, and absorb more energy till failure. However, increasing steel fiber content above the optimal level harmed ductility .Whilst the use of normal concrete in column C2 decreased the ductility by 5.3% when compared with C1 that the brittle nature of concrete did not enable the specimen to withstand high nonlinear displacements. The slight decrease in ductility does not adversely affect the overall structural behavior, especially when the high load capacity gained is taken into consideration. The problem of low ductility of normal concrete has been distinguished and solved by [29] using nano-material-based concrete.

Stiffness criteria

The ability of a material to resist deformations under the applied loads is called stiffness. Material or geometric properties of any section affect positively or negatively on its stiffness under different load scenarios. Theoretically, the secant stiffness of a member can be calculated through the slope of a line starting from the origin and passing through a point of 0.75 of the ultimate load on the load displacement polynomial [30]. The flexural stiffness criterion of each column is as provided in Table 8.

Table 8. Stiffness criteria of the tested columns

Specimen symbol	Load of 0.75 from peak load (kN)	Displacement at 0.75 of peak load (mm)	Stiffness criteria (kN/mm)
C_1	15.75	4.47	3.52
C_2	67.5	6.47	10.43
C_3	85.5	7.21	11.86
C_4	98.25	5.41	18.16
C_5	78	5.46	14.29

It is obvious that the increase in the cross-sectional area of CFAT columns through filling raised their stiffness. As concluded by [31], the stiffness index of column C2, which was filled with normal concrete, increased by 196.3% when compared with column C1 due to the large area of concrete added to the section, which provides high stiffness against the applied loads. In addition, the use of SFC on 0.5,1, and 1.5% raised the stiffness of columns C3, C4, and C5 by 13.7, 74.1, and 37% when compared with column C2 filled with normal concrete and by 236.9, 415.9, and 306% when compared with the hollow column C1. This was also mentioned by [28,29]. The steel fiber normally raises the concrete compressive strength. Also, the additional capacity provided by the ability of steel fibers to maintain most of the concrete stiffness by load redistribution and energy absorption, especially in the elasto-plastic phase, has a positive effect on stiffness indices.

CONCLUSIONS

After the presentation of an experimental study focused on the structural behavior of CFAT columns under axial loads, the following can be deduced:

- Despite their lower yield stress, the aluminum hollow section can be used as a structural member after filling with some types of concrete based on adequate strength, good ductility, and high durability.
- Filling CFAT columns with normal concrete of the lowest structural strength experienced an increase of 328.6% and 196.3% in load capacity and stiffness when compared with hollow sections, as the additional concrete area provides high stiffness throughout the column height and prevents local buckling at earlier loads.
- SFC of 0.5 to 1.5% volume fractions raised the peak load and stiffness by 15.6 to 45.6% and 13.7 to 74.1% due to the increase of concrete strength and the rather fair load redistribution produced by steel fibers.

- The ductility indices of CFAT columns decreased by 5.3% for normal concrete owing to the brittle nature, with SFC, an increase of 9.1 to 42.4% occurred, attributed to the ability of steel fibers to absorb more elasto-plastic deformations till failure.
- Tearing at ultimate load appeared in CFAT columns with normal concrete, while SFC produced local buckling at higher loads without tearing because the steel fibers absorb and reduce the effect of lateral strains on aluminum due to confinement.
- The best structural behavior in terms of load capacity, stiffness, and ductility resulted from using of SFC of 1% volume fraction. Increasing the steel fiber content further harmed the overall structural behavior.

References

1. Mazzolani, F. (1994). Aluminium alloy structures. CRC Press.

2. Zhu, J.-H., & Young, B. (2006). Aluminum alloy circular hollow section beam-columns. Thin-Walled Structures, 44(2), 131–140. https://doi.org/10.1016/j.tws.2006.02.006

3. Lam, D., & Wong, K. K. Y. (2005). Axial capacity of concrete filled stainless steel columns. In Structures Congress 2005: Metropolis and Beyond (pp. 1–11). https://doi.org/10.1061/40753(171)105

4. Jasim, M. H., Nasr, M. S., Beiram, A. A. H., & Heil, S. M. (2024). Mechanical, durability and electrical properties of steel fibers reinforced concrete. Advances in Science and Technology Research Journal, 18.

5. Zhou, F., & Young, B. (2009). Concrete-filled aluminum circular hollow section column tests. Thin-Walled Structures, 47(12), 1272–1280. https://doi.org/10.1016/j.tws.2009.03.014

6. Zhou, F., & Young, B. (2012). Numerical analysis and design of concrete-filled aluminum circular hollow section columns. Thin-Walled Structures, 50, 45–55. https://doi.org/10.1016/j.tws.2011.10.002

7. Al-Mazini, M. A., & Chkhewier, A. H. (2017). Behavior of concrete filled aluminum square and rectangular hollow section columns under axial loads: Experimental and analytical study. Journal of Babylon University/Engineering Sciences, 25, 712–726.

8. Alshimmeri, A. J. H. (2016). Structural behavior of confined concrete filled aluminum tubular (CFT) columns under concentric load. Journal of Engineering, 22, 125–139.

9. Resan, S. F. (2014). Experimental investigation of aluminum-light weight concrete composite columns. Basrah Journal for Engineering Science, 14, 13–25.

10. Wang, F.-C., Zhao, H.-Y., & Han, L.-H. (2019). Analytical behavior of concrete-filled aluminum tubular stub columns under axial compression. Thin-Walled Structures, 140, 21–30. https://doi.org/10.1016/j.tws.2019.03.019

11. Patel, V. I., Liang, Q. Q., & Hadi, M. N. S. (2020). Numerical simulations of circular high strength concrete-filled aluminum tubular short columns incorporating new concrete confinement model. Thin-Walled Structures, 147, 106492. https://doi.org/10.1016/j.tws.2019.106492

12. Ye, Y., Wang, L., Zhang, S.-J., & Zhang, C.-Y. (2021). Compressive behavior of concrete-filled aluminum alloy tube (CFAAT) stub column with inner carbon steel tube. Structures, 32, 701–712. https://doi.org/10.1016/j.istruc.2021.03.026

13. Ali, S. Bin, Kamaris, G. S., & Gkantou, M. (2022). Flexural behaviour of concrete-filled double skin aluminium alloy tubes. Engineering Structures, 272, 114972. https://doi.org/10.1016/j.engstruct.2022.114972

14. Mi, Q., Shu, Q., Wang, F., Liu, P., Zhu, M., & Wang, W. (2024). Experimental study on eccentric compressive behaviors of 6061-T6 aluminum tubular long columns filled with concrete. Engineering Structures, 299, 117040. https://doi.org/10.1016/j.engstruct.2023.117040

15. Yan, X. F., Hao, J. P., & He, M. N. (2024). Behavior of circular concrete-filled double-skin aluminum alloy tubular stub columns: Test, modeling and confinement-based design. Journal of Building Engineering, 95, 110060.

16. American Institute of Steel Construction. (2014). Steel construction manual (14th ed.).

17. ASTM. (2015). ASTM B557M-15: Standard test methods of tension testing wrought and cast aluminum- and magnesium-alloy products [Metric]. American Society for Testing and Materials.

18. Central Organization for Standardization and Quality Control. (1984). Iraqi Specification No. 5: Portland Cement. Baghdad, Iraq.

19.Central Organization for Standardization and Quality Control. (1984). Iraqi Specification No. 45: Aggregate from natural sources used in concrete and construction. Baghdad, Iraq.

20. British Standards Institution. (1983). BS 1881-116: Testing concrete – Part 116: Method for determination of compressive strength of concrete cubes. London, UK.

21. Khan, I. U., Gul, A., Khan, K., & Akbar, S. (2022). Mechanical properties of steel-fiber-reinforced concrete. Engineering Proceedings, 22, 6.

22. Ashokan, A., Rajendran, S., & Dhairiyasamy, R. (2023). A comprehensive study on enhancing the mechanical properties of steel fiber-reinforced concrete through nano-silica integration. Scientific Reports, 13, 20092.

23.Mohammed, A. M., & Abd Sultan, A. (2024). Effects of steel fiber content and maximum coarse aggregate size on mechanical properties of steel fiber reinforced concrete. University of Thi-Qar Journal for Engineering Sciences, 14(1), 107–119. https://doi.org/10.31663/utjes.14.1.669

24. Wafi, A. (2021). Investigation of the behavior of steel tubular columns filled with reactive powder concrete and comparison with ACI design criteria. Kerbala Journal for Engineering Sciences, 1(1), 93–112.

25. Georgantzia, E., Bin Ali, S., Gkantou, M., Kamaris, G. S., Kansara, K. D., & Atherton, W. (2021). Flexural buckling performance of concrete-filled aluminium alloy tubular columns. Engineering Structures, 242, 112546. https://doi.org/10.1016/j.engstruct.2021.112546

26. Ghallab, A. (2014). Ductility of externally prestressed continuous concrete beams. KSCE Journal of Civil Engineering, 18(3), 595–606. https://doi.org/10.1007/s12205-014-0443-0

27. Naji, A. J., Al-Jelawy, H. M., Hassoon, A., & Al-Rumaithi, A. (2022). Axial behavior of concrete filled-steel tube columns reinforced with steel fibers. International Journal of Engineering, 35(9), 1682–1689. https://doi.org/10.5829/ije.2022.35.09c.02

28.Al-Abbas, B., Rasoul, Z. M. R. A., & Hasan, D. (2024). Ductility and shape effect of steel tube column filled with reactive powder concrete. Results in Engineering, 24, 103523. https://doi.org/10.1016/j.rineng.2024.103523

29. Singh, H., Tiwary, A. K., Eldin, S. M., & Ilyas, R. A. (2023). Behavior of stiffened concrete-filled steel tube columns infilled with nanomaterial-based concrete subjected to axial compression. Journal of Materials Research and Technology, 24, 9580–9593. https://doi.org/10.1016/j.jmrt.2023.05.135

30.Muthuswamy, K. R., & Thirugnanam, G. S. (2014). Structural behaviour of hybrid fibre reinforced concrete exterior beam-column joint subjected to cyclic loading. International Journal of Civil & Structural Engineering, 4(3), 262–273.

31. Hassooni, A. N., & Al Zaidee, S. R. (2022). Behavior and strength of composite columns under the impact of uniaxial compression loading. Engineering, Technology & Applied Science Research, 12(4), 8843–8849.